



A MATTER OF TIME

Bizarre forms of matter called time crystals were once thought to be physically impossible. But thanks to a loophole, they now exist.

BY ELIZABETH GIBNEY

Christopher Monroe spends his life poking at atoms with light. He arranges them into rings and chains and then massages them with lasers to explore their properties and make basic quantum computers. Last year, he decided to try something seemingly impossible: to create a time crystal.

The name sounds like a prop from *Doctor Who*, but it has roots in actual physics. Time crystals are hypothetical structures that pulse without requiring any energy — like a ticking

clock that never needs winding. The pattern repeats in time in much the same way that the atoms of a crystal repeat in space. The idea was so challenging that when Nobel prizewinning physicist Frank Wilczek proposed the provocative concept¹ in 2012, other researchers quickly proved there was no way to create time crystals.

But there was a loophole — and researchers in a separate branch of physics found a way to exploit the gap. Monroe, a physicist at the University of Maryland in College Park, and

ILLUSTRATION BY PETER CROWTHER

his team used chains of atoms they had constructed for other purposes to make a version of a time crystal² (see ‘How to create a time crystal’). “I would say it sort of fell in our laps,” says Monroe.

And a group led by researchers at Harvard University in Cambridge, Massachusetts, independently fashioned time crystals out of ‘dirty’ diamonds³. Both versions, which are published this week in *Nature*, are considered time crystals, but not how Wilczek originally imagined. “It’s less weird than the first idea, but it’s still fricking weird,” says Norman Yao, a physicist at the University of California, Berkeley, and an author on both papers.

They are also the first examples of a remarkable type of matter — a collection of quantum particles that constantly changes, and never reaches a steady state. These systems draw stability from random interactions that would normally disrupt other kinds of matter. “This is a

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new kind of order, one that was previously thought impossible. That’s extremely exciting,” says Vedika Khemani, part of the Harvard team and previously part of the group that originally theorized the existence of the new kind of state. Experimental physicists are already plotting how to exploit the traits of these strange systems in quantum computers and super-sensitive magnetic sensors.

BREAK TIME

Wilczek dreamt up time crystals as a way to break the rules. The laws of physics are symmetrical in that they apply equally to all points in space and time. Yet many systems violate that symmetry. In a magnet, atomic spins line up rather than pointing in all directions. In a mineral crystal, atoms occupy set positions in space, and the crystal does not look the same if it is shifted slightly. When a transformation causes properties to change, physicists call that symmetry-breaking, and it is everywhere in nature — at the root of magnetism, superconductivity and even the Higgs mechanism that gives all particles mass.

In 2012, Wilczek, now at Stockholm University, wondered why symmetry never broke spontaneously in time and whether it would be possible to create something in which it did. He called it a time crystal. Experimentalists imagined a quantum version of this entity as perhaps a ring of atoms that would rotate endlessly, cycling and returning to its initial configuration. Its properties would be endlessly synchronized in time, just as atom positions are correlated in a crystal. The system would be in its lowest energy state, but its movement would require no external force. It would, in essence, be a perpetual-motion machine, although not one that produces usable energy.

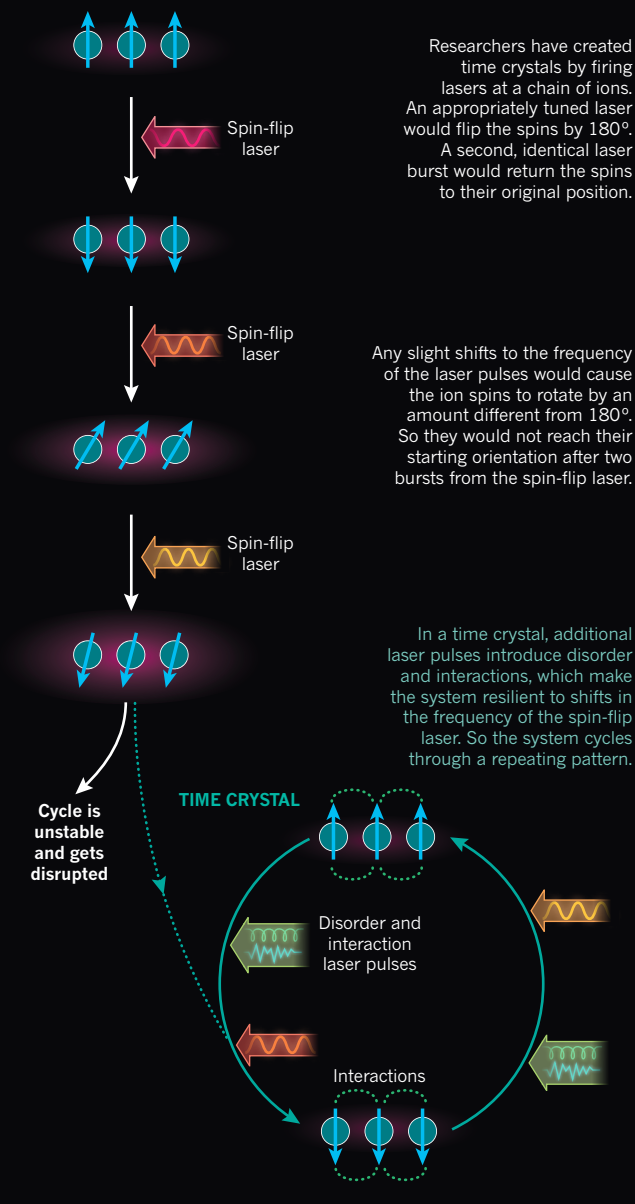
“From a first glance at the idea, one would say this has to be wrong,” says Yao. Almost by definition, a system in its lowest energy state does not vary in time. If it did, that would mean it had excess energy to lose, says Yao, and the rotation would soon halt. “But Frank convinced the community that the problem was more subtle than maybe it seemed to be,” he says. Perpetual motion was not without precedent in the quantum world: in theory, superconductors conduct electricity forever (although the flow is uniform, so they show no variation in time).

These conflicting issues swam around the head of Haruki Watanabe as he stepped out of the first oral exam for his PhD at Berkeley. He had been presenting work on symmetry breaking in space, and his supervisor asked him about the wider implications of Wilczek’s time crystal. “I couldn’t answer the question in that exam, but it interested me,” says Watanabe, who doubted such an entity was even feasible. “I wondered, ‘how can I convince people that it’s not possible?’”

Together with physicist Masaki Oshikawa at the University of Tokyo, Watanabe began trying to prove his intuitive answer in a mathematically rigorous way. By phrasing the problem in terms of correlations in space and time between distant parts of the system, the pair derived a

HOW TO CREATE A TIME CRYSTAL

Mineral crystals break symmetry in space because their atoms occupy fixed positions, so they look different when shifted. They also resist changes to their spatial structure. ‘Time crystals’ break symmetry in the time domain: they change from one moment to another, also with a repeating pattern that is resilient.



theorem in 2015 showing that time crystals were impossible to create for any system in its lowest-energy state⁴. The researchers also verified that time crystals were impossible for any system in equilibrium — one that has reached a steady state of any energy.

To the physics community, the case was clear cut. “That seemed to be a no-go,” says Monroe. But the proof left a loophole. It did not rule out time crystals in systems that have not yet settled into a steady state and are out of equilibrium. Around the world, theorists began thinking about ways to create alternative versions of time crystals.

PARTICLE SOUP

When the breakthrough came, it arrived from an unlikely corner of physics, where researchers weren’t thinking about time crystals at all.

Shivaji Sondhi, a theoretical physicist at Princeton University, New

Jersey, and his colleagues were looking at what happened when certain isolated quantum systems, made of soups of interacting particles, are repeatedly given a kick. Textbook physics says that the systems should heat up and descend into chaos. But in 2015, Sondhi's team predicted that under certain conditions, they would instead club together to form a phase of matter that doesn't exist in equilibrium — a system of particles that would show subtle correlations never seen before — and that would repeat a pattern in time⁵.

That proposal caught the attention of Chetan Nayak, one of Wilczek's former students, now at the University of California, Santa Barbara, and at Microsoft's nearby Station Q. Nayak and his colleagues soon realized that this strange form of out-of-equilibrium matter would also be a type of time crystal⁶. But not Wilczek's kind: it would not be in its lowest energy state, and it would require a regular kick to pulse. But it would gain a steady rhythm that doesn't match that of the instigating kick, and that means it would break time symmetry.

"It's like playing with a jump rope, and somehow our arm goes around twice but the rope only goes around once," says Yao. This is a weaker kind of symmetry breaking than Wilczek imagined: in his, the rope would oscillate all by itself.

When Monroe heard about this proposed system, he initially didn't understand it. "The more I read about it, the more intrigued I became," he says.

Last year, he set about trying to form his atoms into a time crystal. The recipe was incredibly complex, but just three ingredients were essential: a force repeatedly disturbing the particles, a way to make the atoms interact with each other and an element of random disorder. The combination of these, Monroe says, ensures that particles are limited in how much energy they can absorb, allowing them to maintain a steady, ordered state.

In his experiment, this meant repeatedly firing alternating lasers at a chain of ten ytterbium ions: the first laser flips their spins and the second makes the spins interact with each other in random ways. That combination caused the atomic spins to oscillate, but at twice the period they were being flipped. More than that, the researchers found that even

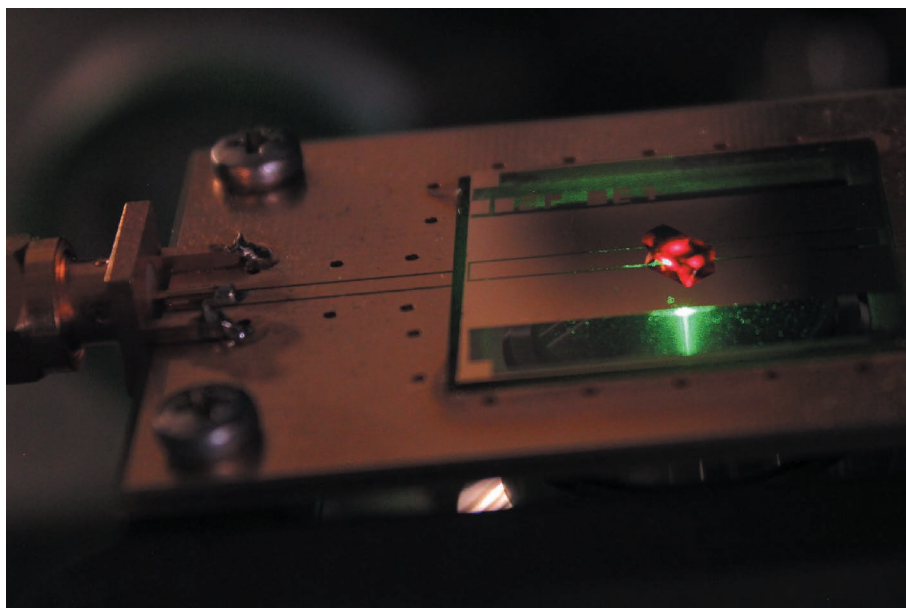
"THIS IS AN INTRIGUING DEVELOPMENT, BUT TO SOME EXTENT IT'S AN ABUSE OF THE TERM."

if they started to flip the system in an imperfect way, such as by slightly changing the frequency of the kicks, the oscillation remained the same. "The system still locked at a very stable frequency," says Monroe. Spatial crystals are similarly resistant to any attempt to nudge their atoms from their set spacing, he says. "This time crystal has the same thing."

At Harvard, physicist Mikhail Lukin tried to do something similar, but in a very different system — a 3D chunk of diamond. The mineral was riddled with around 1 million defects, each harbouring a spin. And the diamond's impurities provided a natural disorder. When Lukin and his team used microwave pulses to flip the spins, they saw the system respond at a fraction of the frequency with which it was being disturbed.

Physicists agree that the two systems spontaneously break a kind of time symmetry and therefore mathematically fulfil the time-crystal criteria. But there is some debate about whether to call them time crystals. "This is an intriguing development, but to some extent it's an abuse of the term," says Oshikawa.

Yao says that the new systems are time crystals, but that the definition needs to be narrowed to avoid including phenomena that are already



Illumination with green light reveals a time crystal formed in a network of electron spins (red) within the defects of a diamond.

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well understood and not nearly so interesting for quantum physicists.

But Monroe and Lukin's creations are exciting for different reasons, too, says Yao. They seem to be the first, and perhaps simplest, examples of a host of new phases that exist in relatively unexplored out-of-equilibrium states, he says. They could also have several practical applications. One could be quantum simulation systems that work at high temperatures. Physicists often use entangled quantum particles at nanokelvin temperatures, close to absolute zero, to simulate complex behaviours of materials that cannot not be modelled on a classical computer. Time crystals represent a stable quantum system that exists way above these temperatures — in the case of Lukin's diamond, at room temperature — potentially opening the door to quantum simulations without cryogenics.

Time crystals could also find use in super-precise sensors, says Lukin. His lab already uses diamond defects to detect tiny changes in temperature and magnetic fields. But the approach has limits, because if too many defects are packed in a small space, their interactions destroy their fragile quantum states. In a time crystal, however, the interactions serve to stabilize, rather than disrupt, so Lukin could harness millions of defects together to produce a strong signal — one that is able to efficiently probe living cells and atom-thick materials.

The same principle of stability from interactions could apply more widely in quantum computing, says Yao. Quantum computers show huge promise, but have long struggled with the opposing challenges of protecting the fragile quantum bits that perform calculations, yet keeping them accessible for encoding and reading out information. "You can ask yourself in the future whether one could find phases where interactions stabilize these quantum bits," says Yao.

The story of time crystals is a beautiful example of how progress often happens when different strands of thought come together, says Roderich Moessner, director of the Max Planck Institute for the Physics of Complex Systems in Dresden, Germany. And it may be, he says, that this particular recipe proves to be just one of many ways to cook up a time crystal. ■

Elizabeth Gibney is reporter for *Nature* in London.

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